Nebulae around runaway stars

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in collaboration with

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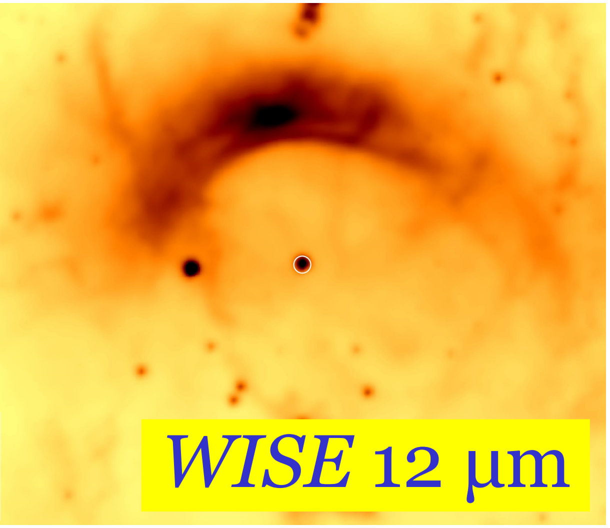
Runaway stars

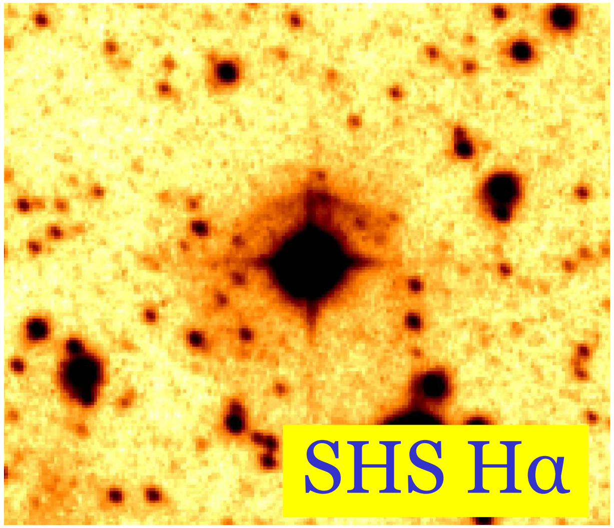
- about 20 % of O stars are in the field (Gies 1987)
- space velocities range from ≈10 to several 100 km/s
- about 20-30 % of the field O stars have velocities >30 km/s (runaway stars) (Blaauw 1961; Gies 1987)
- about 70 % of runaway O stars are binary systems (Chini et al. 2012)
- about 30-40 % of all O stars interact with a companion while they are still on the main sequence (Sana et al. 2012)

Bow shocks around runaway stars

ζ Oph (O9.2 IVnn)

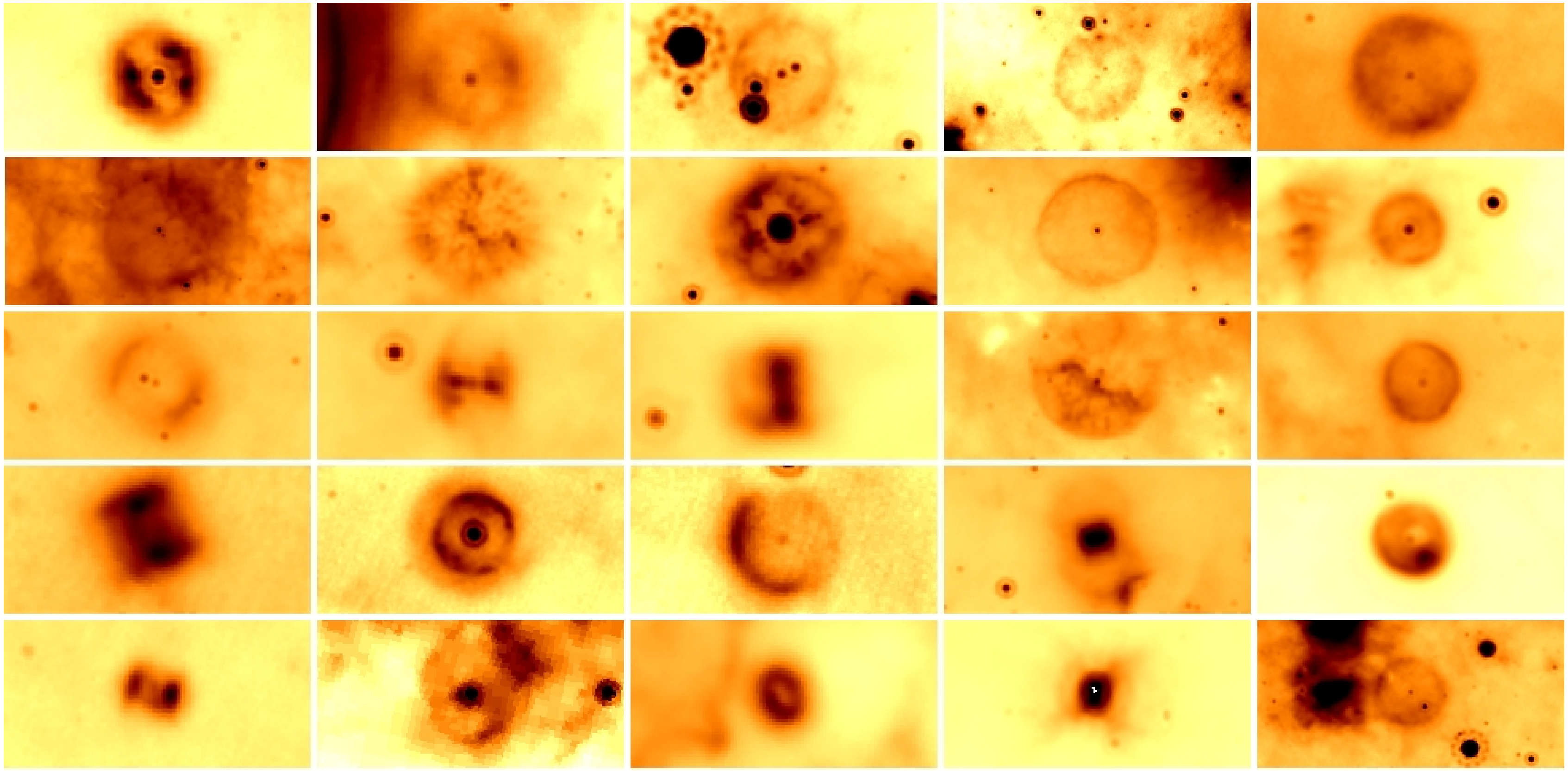


BD+43°3654(O4If)



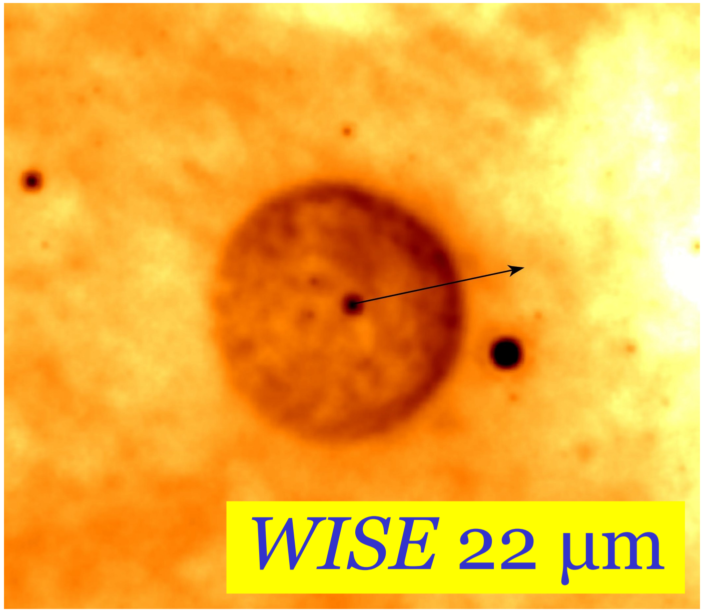
IRC-10414 (M7I)

Infrared shells around LBV and WR stars

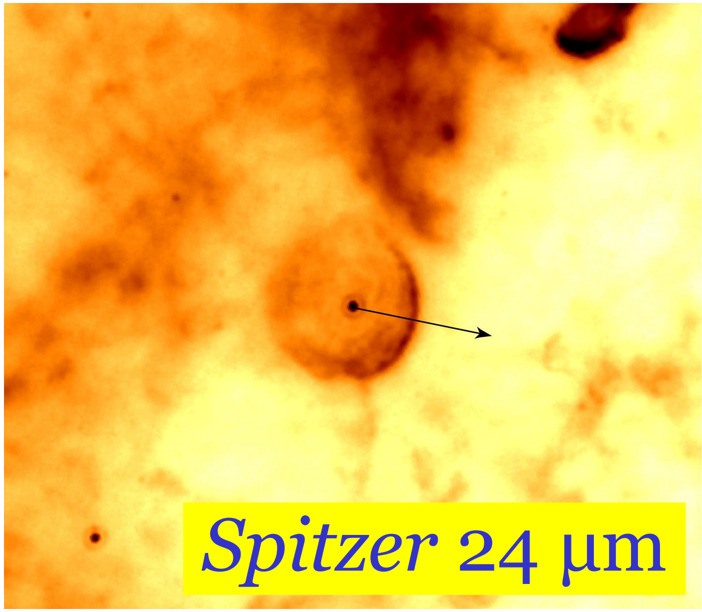


Gvaramadze et al. 2010

Circumstellar nebulae around runaway Wolf-Rayet stars

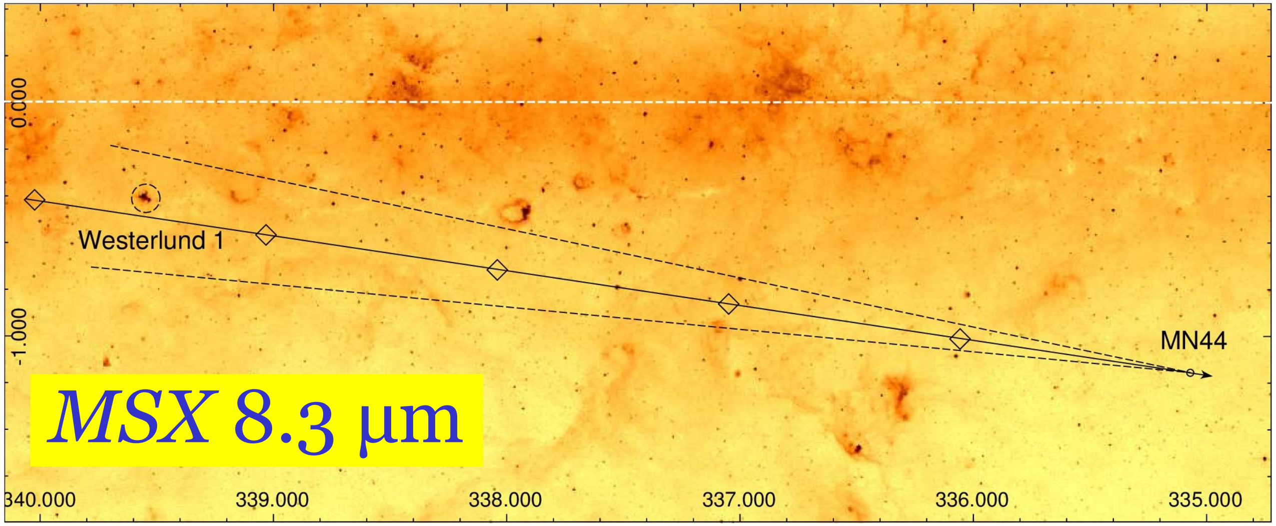


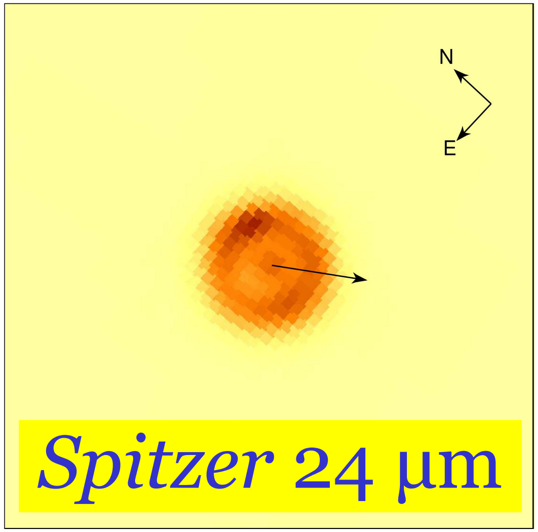
WR 16 (WN8h)



WR 138a (WN8h)

MN44: an LBV running away from Westerlund 1

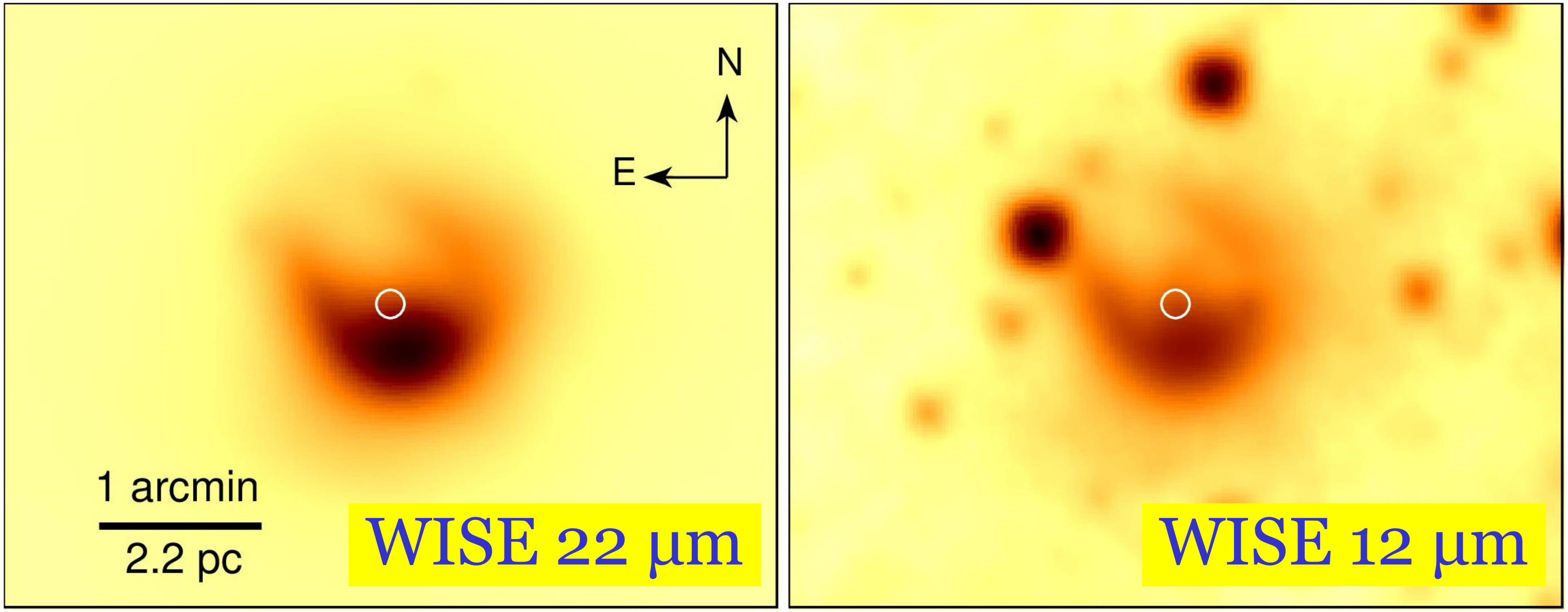




υ_{tr}=74±3 km/s, l≈310 pc => t_{kin}=4.2 Myr
(age of Westerlund 1 ≈5 Myr)

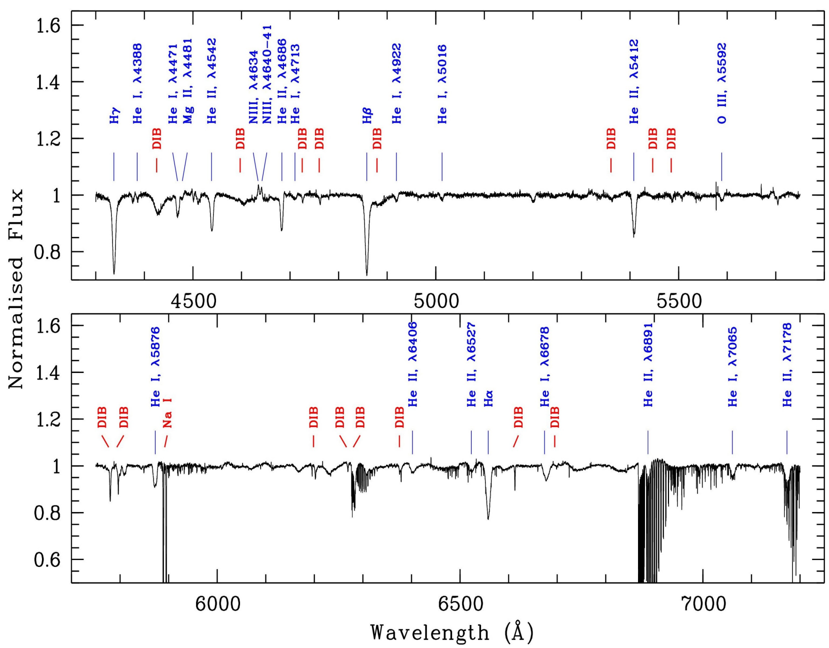
Gvaramadze 2018

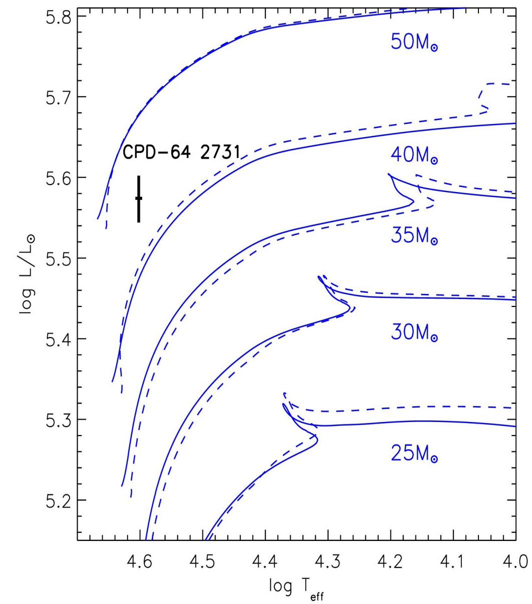
CPD-64°2731: a massive spun-up and rejuvenated high-velocity runaway star



Gvaramadze et al. 2019

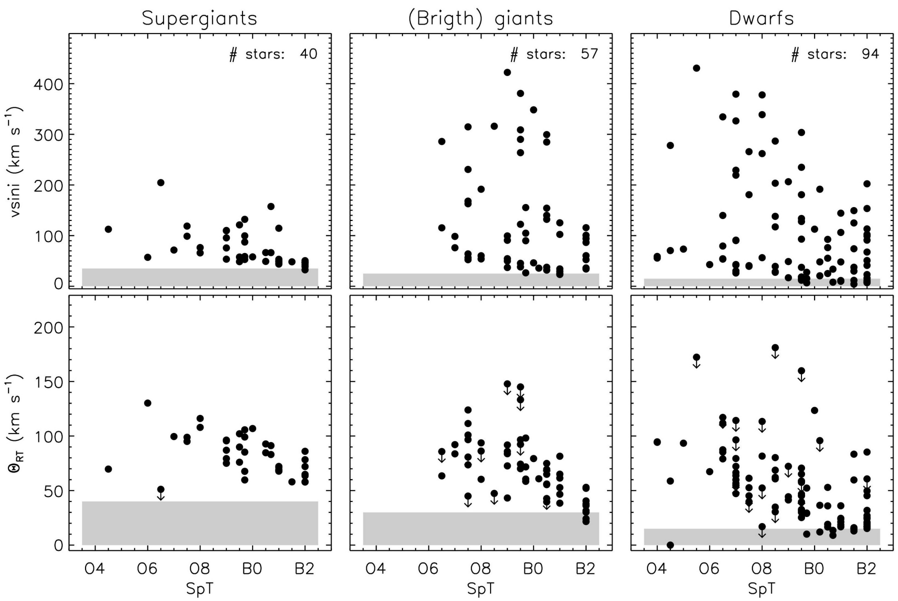
CPD-64°2731

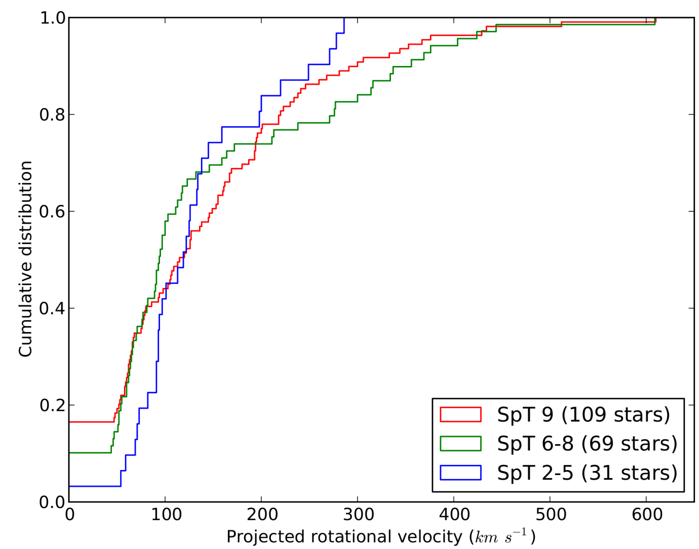




- O5.5 Vn((f)), M≈40 M_{sun}, υ sin i≈300 km/s, υ_r≈-136 km/s
- nitrogen abundance is enhanced by a factor of 6-8 => υ_{init}≈400 km/s, age ≤3 Myr

Rotational velocities of O stars





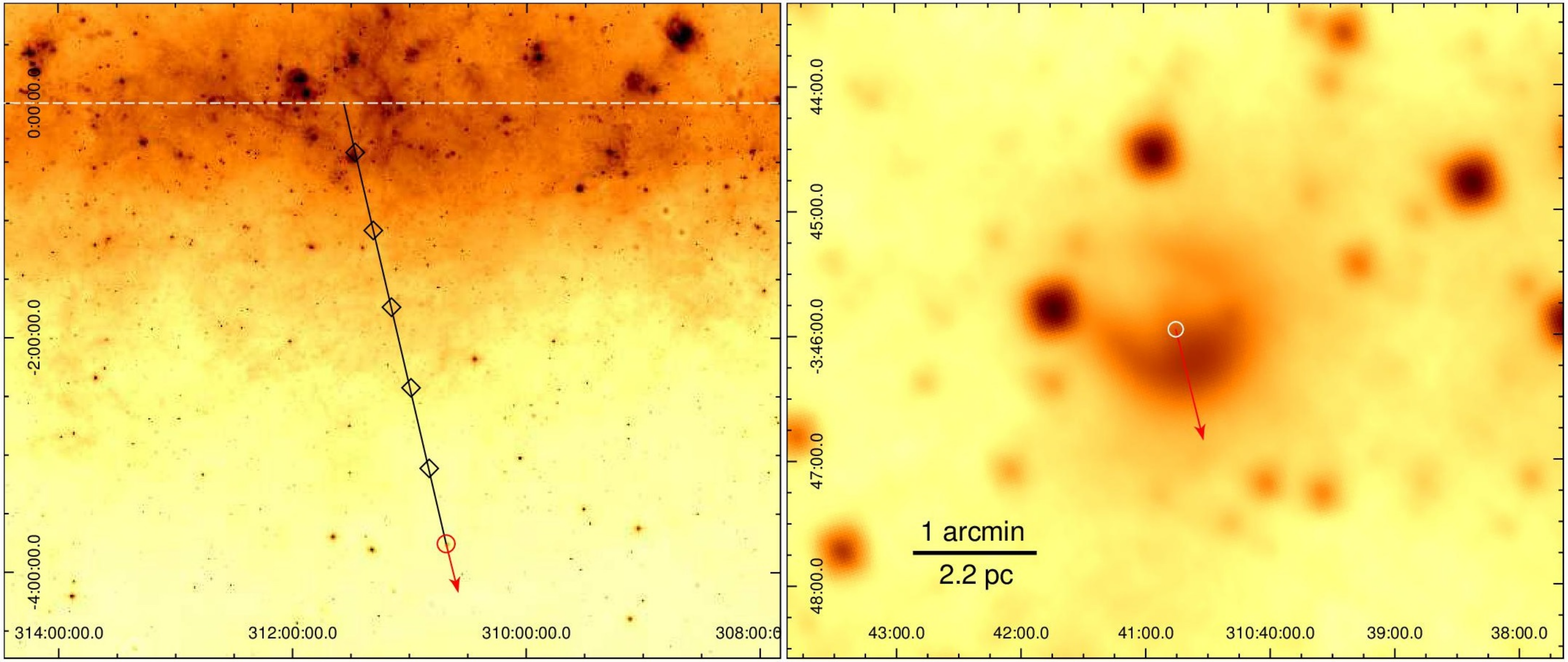
Galactic O stars

(Simon-Diaz & Herrero 2014)

LMC O stars

(Ramirez-Agudelo et al. 2013)

CPD-64°2731



d=7.5 kpc, z=490 pc, v_{tr}=89 km/s

=> $t_{kin}=z/v_{tr}$=5.7 Myr (age≤3 Myr)

CPD-64°2731

$\log(\dot{M}/M_{sun}\ yr^{-1})$=-5.96,

υ_∞=2900 km/s,

υ_r=-136 km/s,

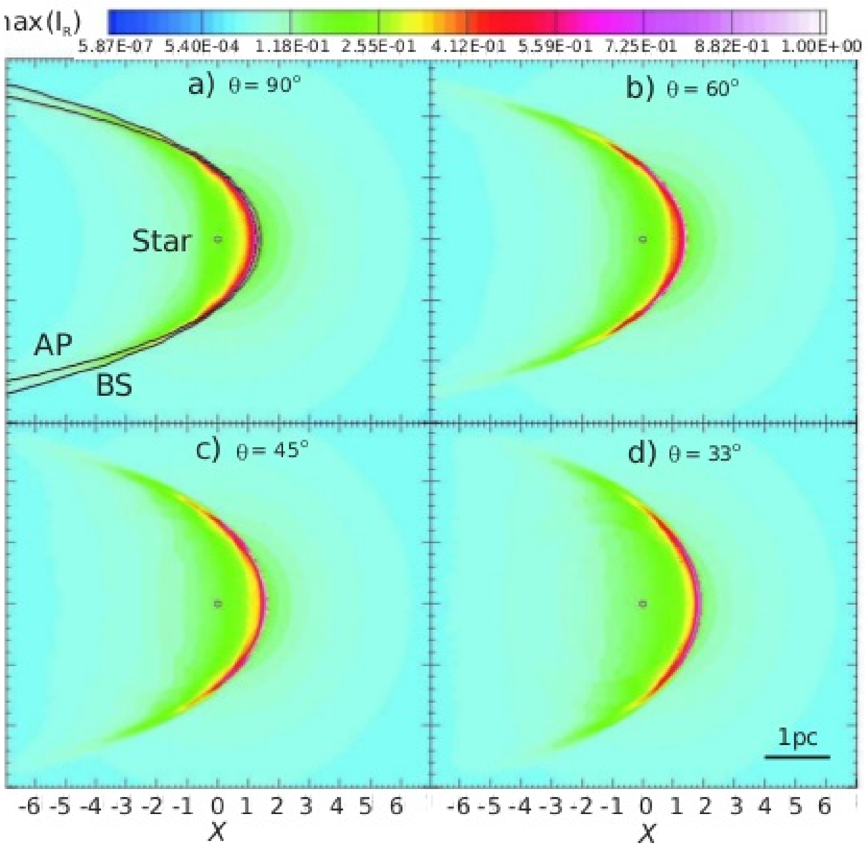
υ_{tr}=89 km/s,

υ_*=163 km/s,

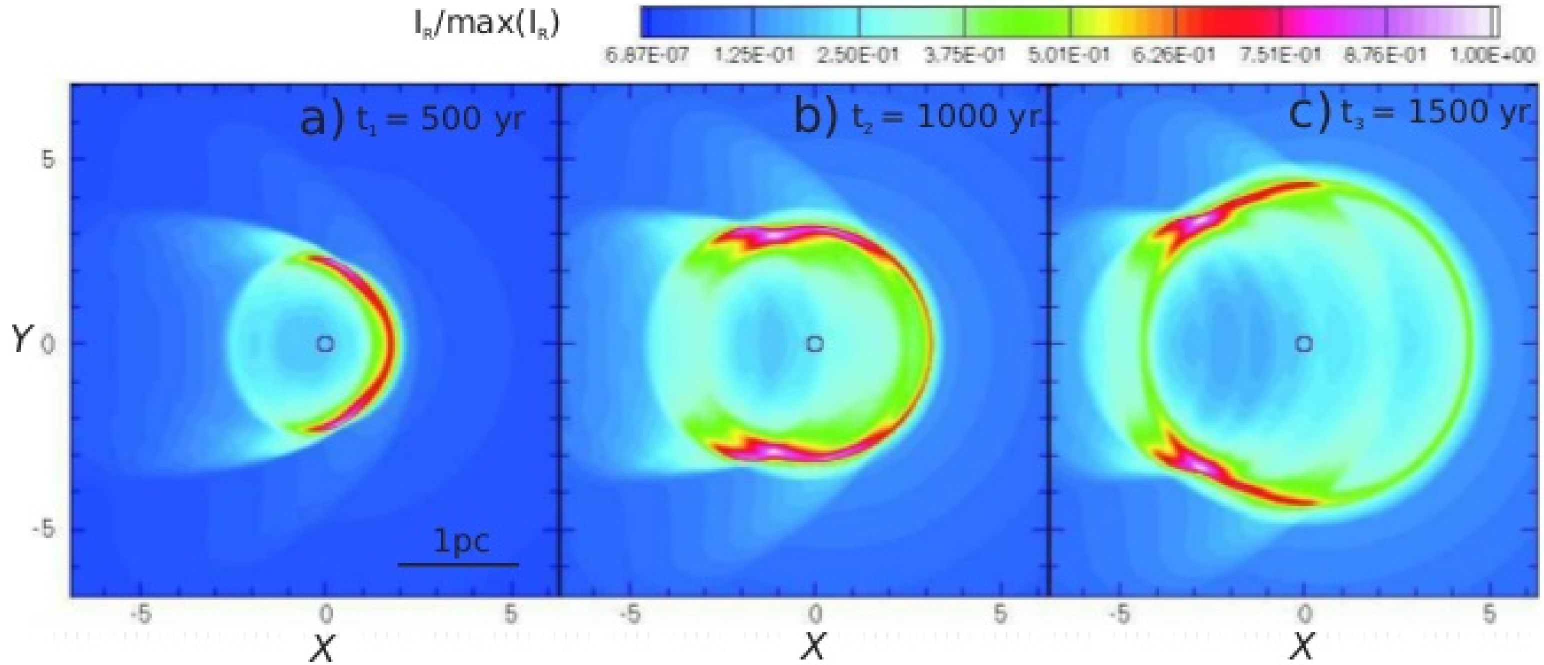
θ=33°

R_o=0.9 pc

=> n_{ISM}=0.4 cm^{-3}



CPD-64∘2731



- $t<t_*$: runaway binary composed of two 20 M_{sun} stars (fast wind); n_{ISM}=0.04 cm^{-3} (Dickey & Lockman 1990)
- $t=t_*$: merger => slow wind
- $t= t_*$+several 1000 yr: fast wind with parameters of CPD-64∘2731

CPD-64$\circ$2731

The extremely high rotational velocity and the kinematic age of CPD−64$\circ$2731 (exceeding its age derived from single star models by a factor of 2), imply that this star is a rejuvenated and spun-up binary product. The geometry of the nebula and the almost central location of the star within it argue against a pure bow shock interpretation for the nebula. Instead, we suggest that the binary interaction happened recently, thereby creating the nebula, with a cavity blown by the current fast stellar wind.

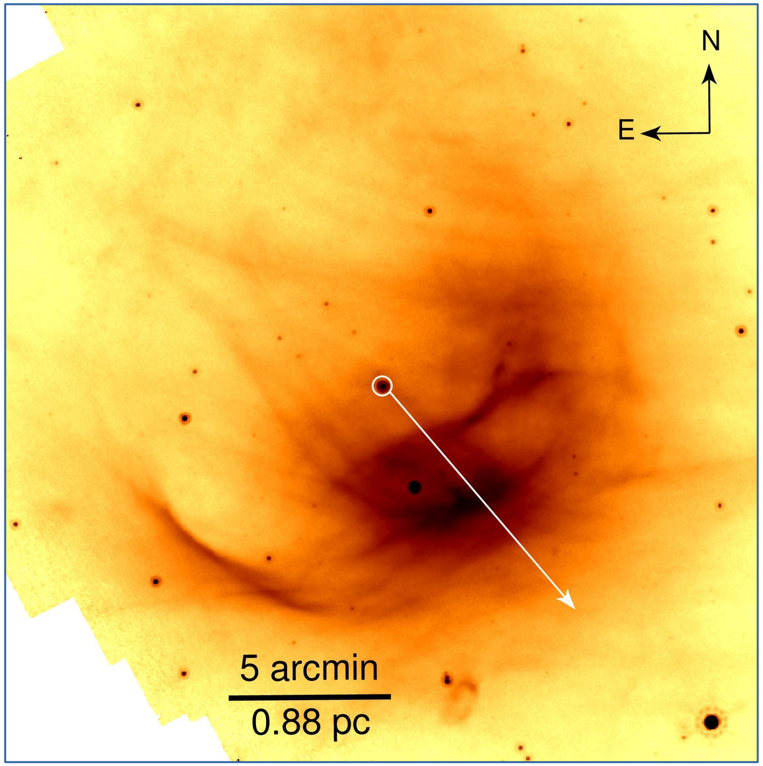
λ Cep: a merger product?

SpT=O6.5 I(n)fp

$M \approx$ 45-60 M_{sun}

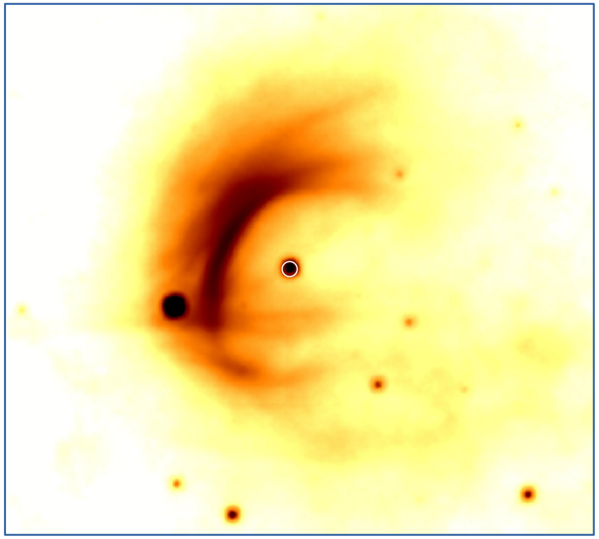
υ_{rot}=200 km/s

υ_*=60 km/s

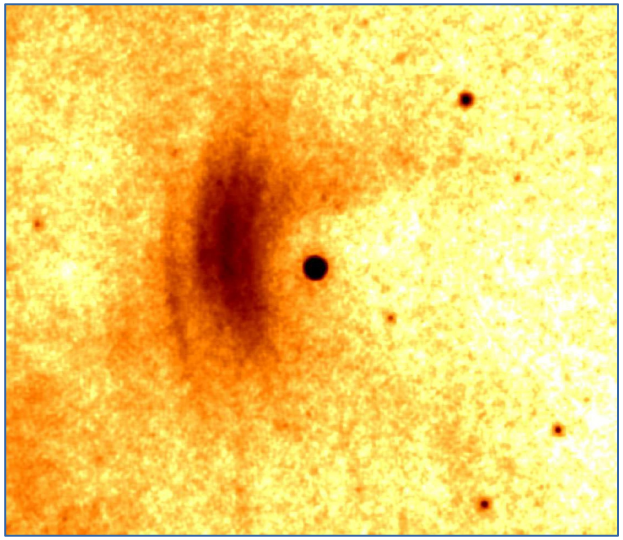


Gvaramadze et al. 2019

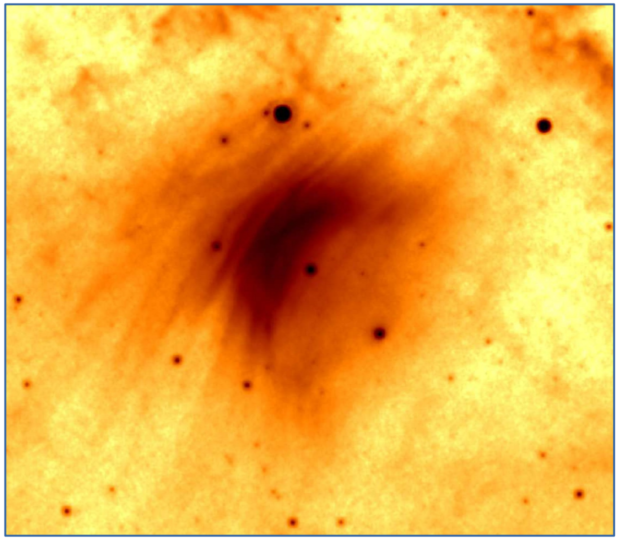
Cirrus-like bow shocks



κ Cas (B1 Ia)



β CMa (B1 II-III)

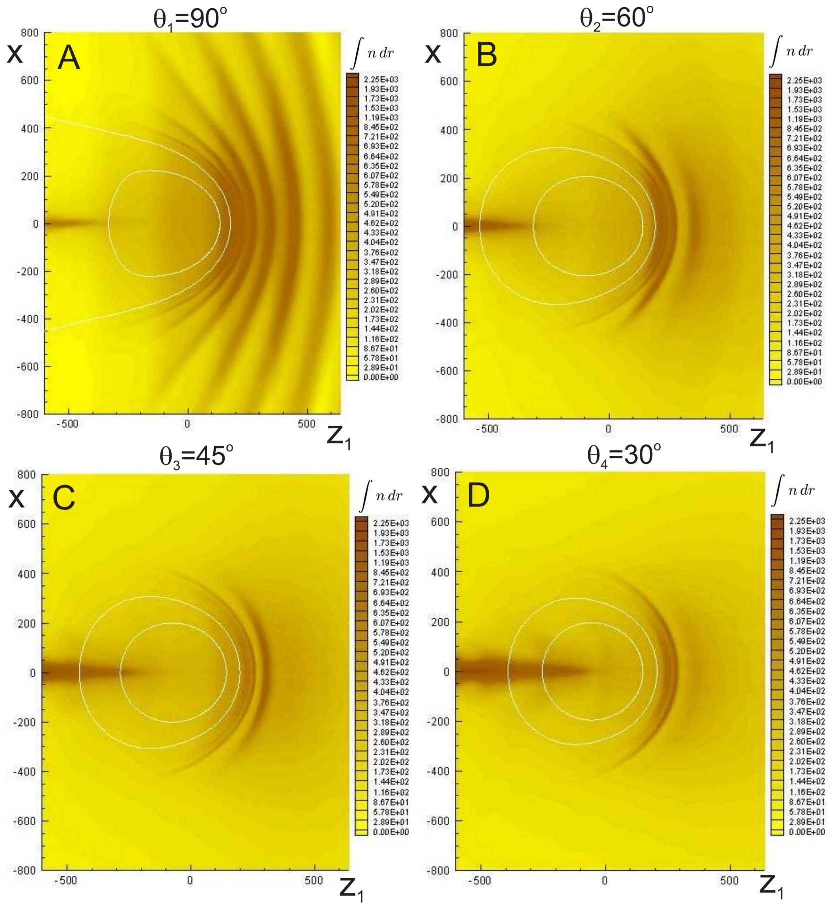


θ Car (B0 Vp)

Cirrus-like bow shocks

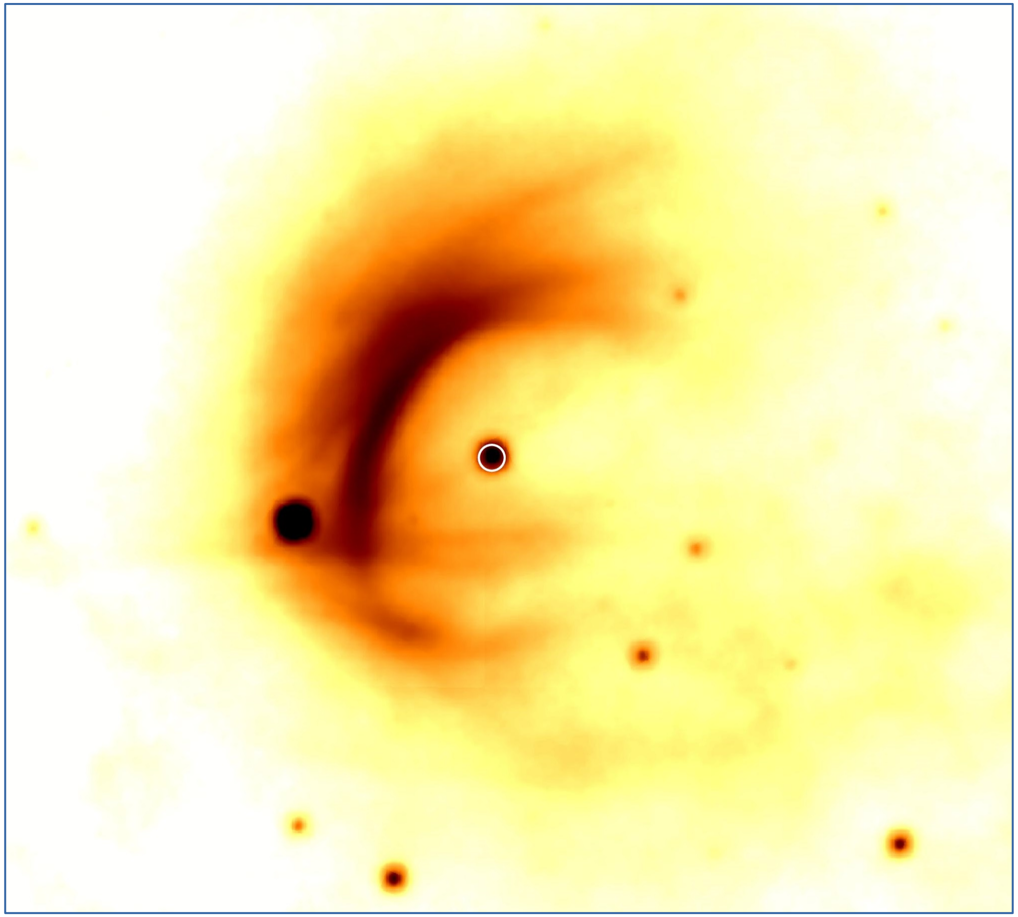
- gyrorotation of charged dust grains in the interstellar magnetic field produces non-monotonic spatial distribution of the dust

- the number of filaments depends on the size of dust grains and on the line of sight

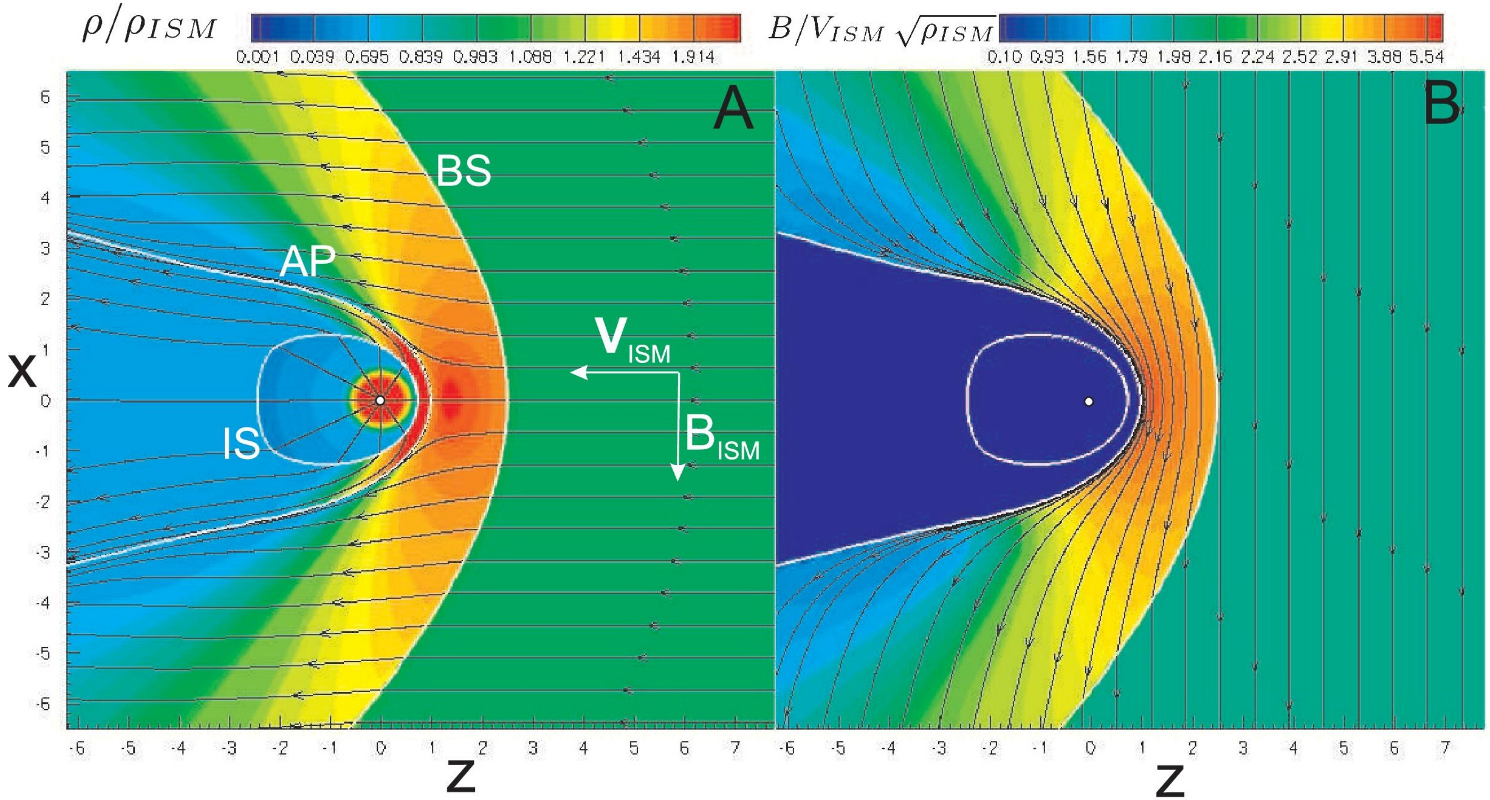


Katushkina et al. 2017

κ Cas

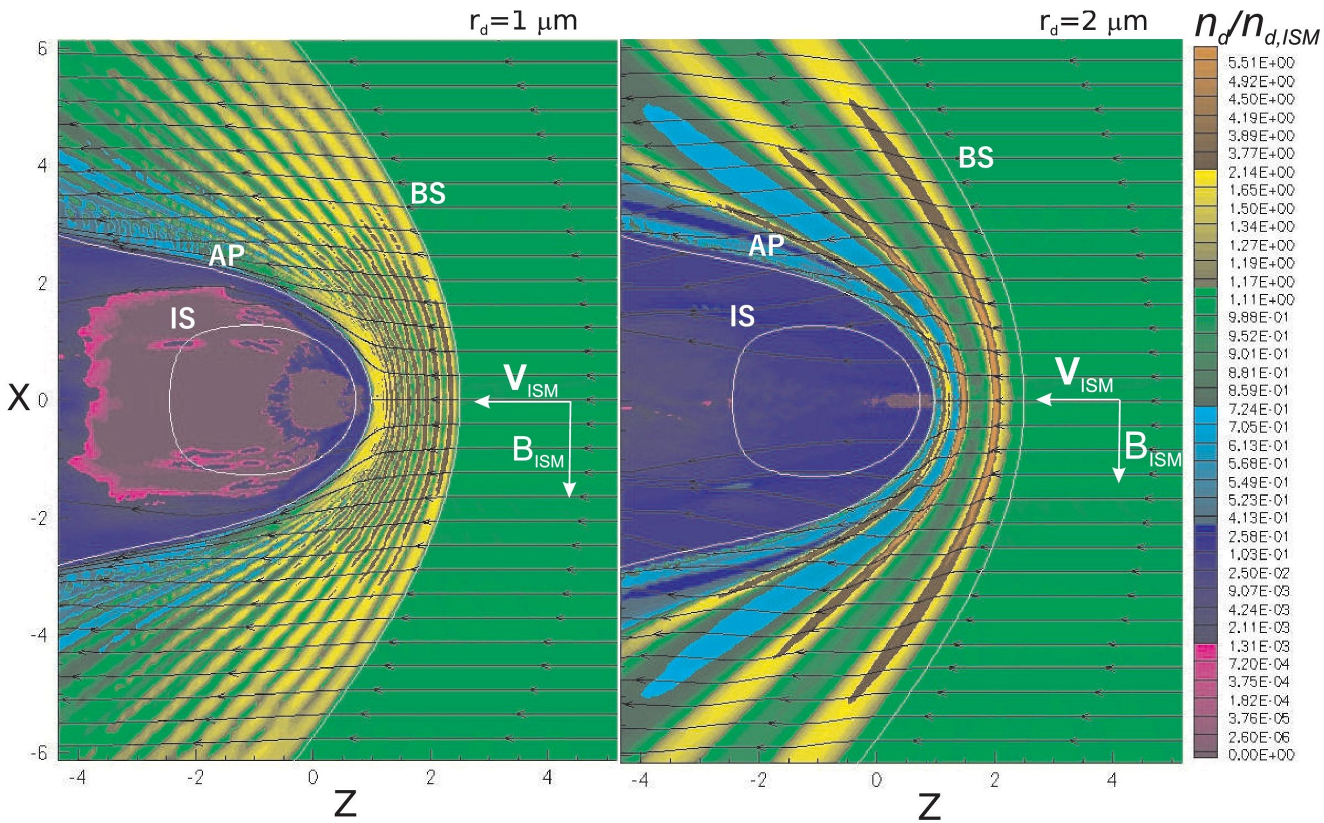


Cirrus-like bow shocks

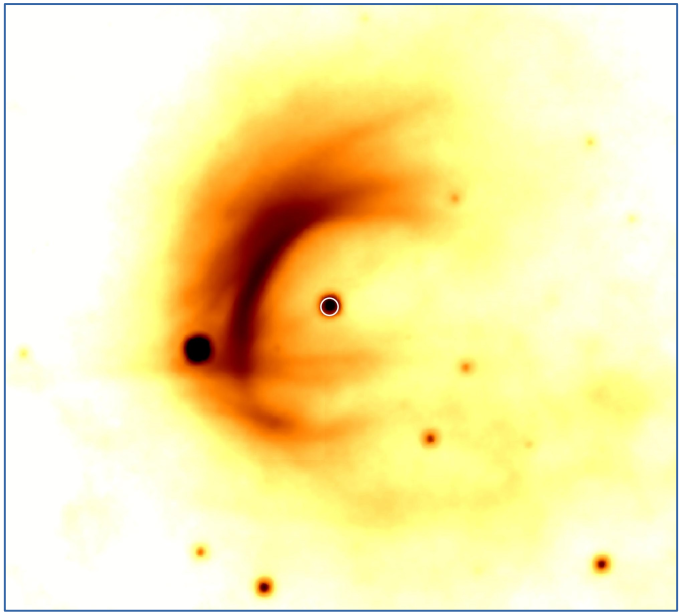


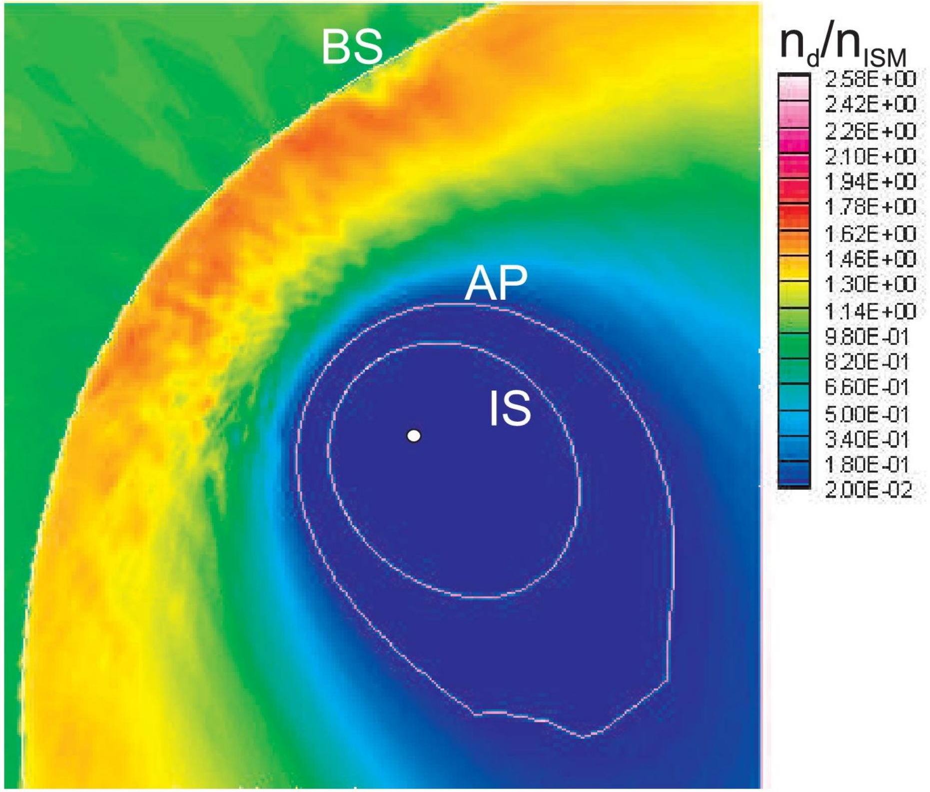
Katushkina et al. 2018

Cirrus-like bow shocks



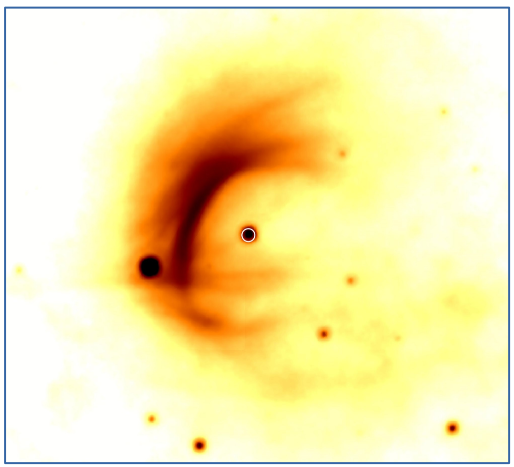
Cirrus-like bow shocks

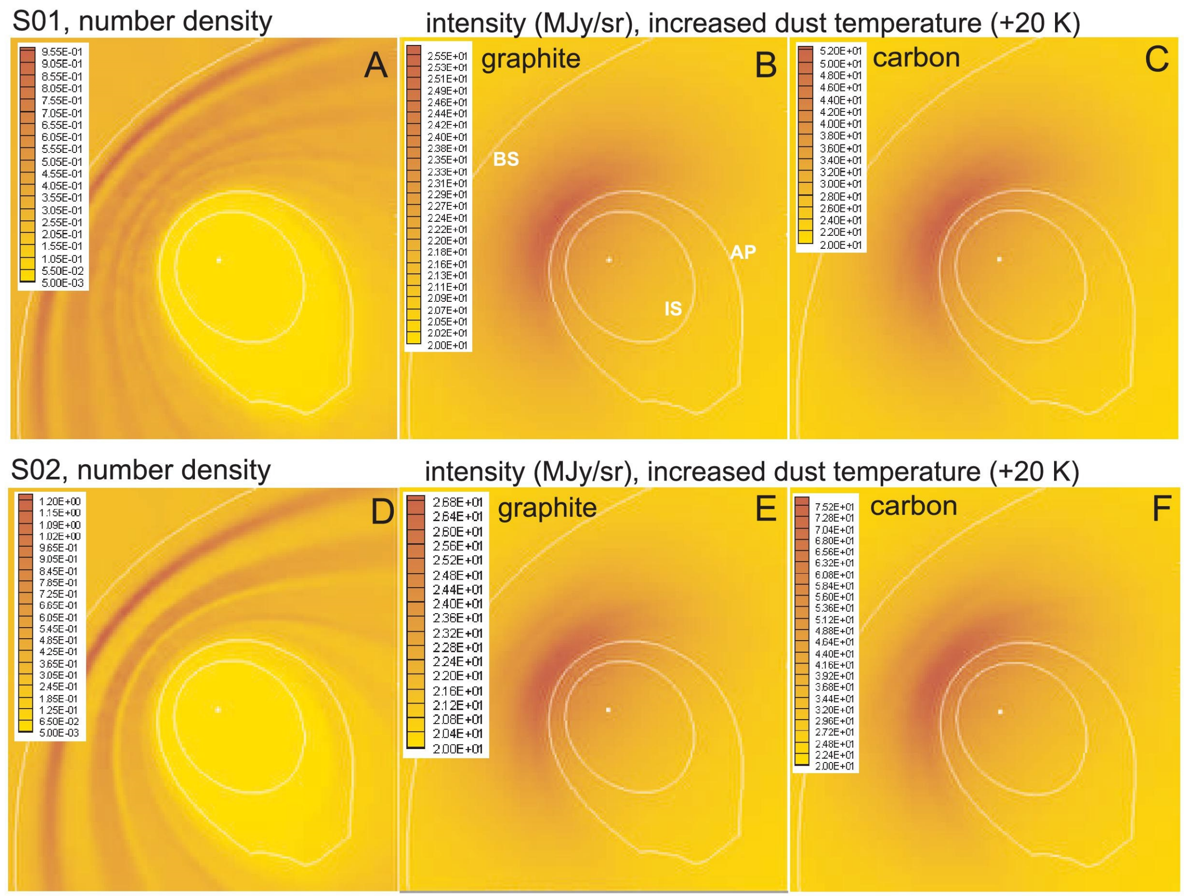




power-law MRN size distribution
(Mathis, Rumpl & Nordsieck 1977)

Cirrus-like bow shocks



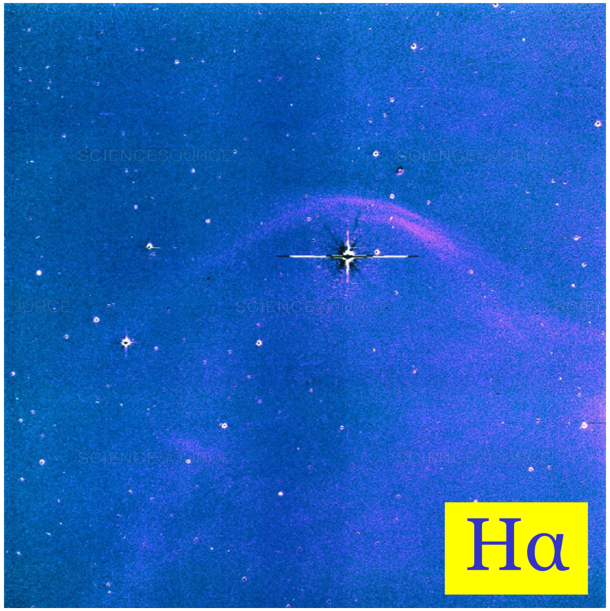


$n_{\mathrm{ISM}} \approx 10\ \mathrm{cm}^{-3}$, $B_{\mathrm{ISM}} \approx 20\text{-}30\ \mu\mathrm{G}$

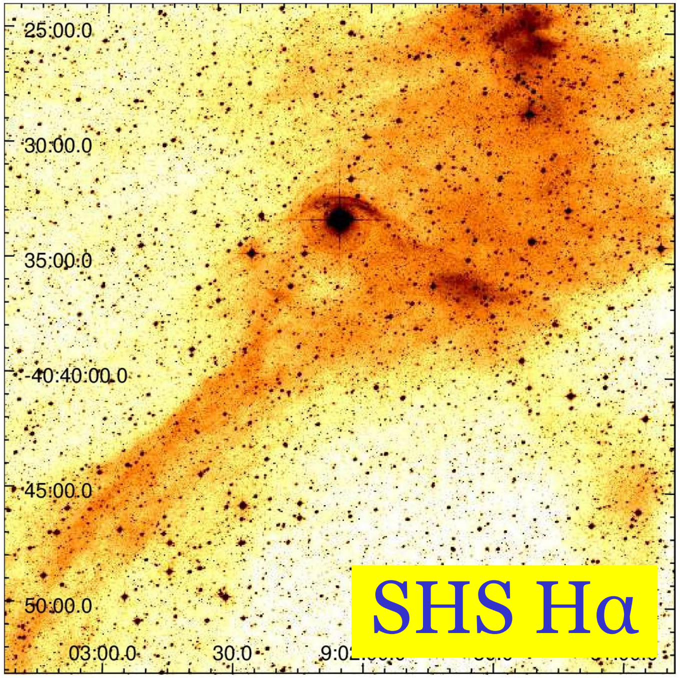
Cirrus-like bow shocks

It is found that the model results with the classical MRN (Mathis, Rumpl & Nordsieck 1997) size distribution of dust in the ISM do not match the observations, and that the observed filamentary structure of the bow shock can be reproduced only if the dust is composed mainly of big (μm-sized) grains.

Circumstellar structures around Vela X-1



Kaper et al. 1997



Gvaramadze et al. 2018

$\upsilon_{\mathbf{tr}}$≈46 km/s, υ_{r}≈-30 km/s, υ_{*}≈54 km/s, θ=60°

Circumstellar structures around Vela X-1

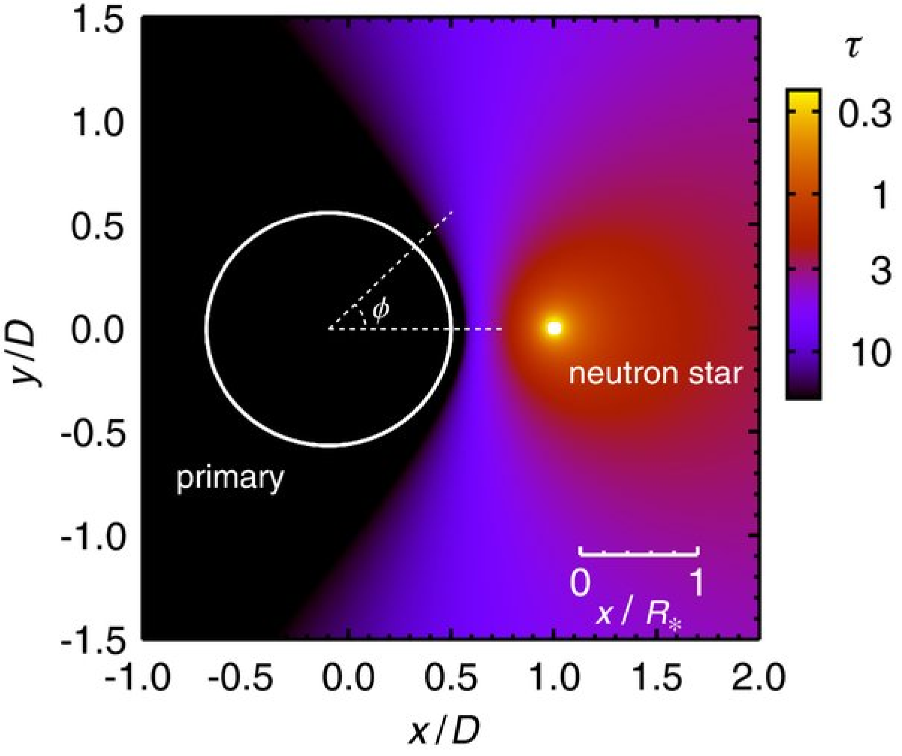
3D MHD simulations of interaction between Vela X-1 and a wedge-like layer for three limiting cases:

- the stellar wind and the ISM were treated as pure hydrodynamic flows (model 1)
- a homogeneous *B*-field was added to the ISM, while the stellar wind was assumed to be unmagnetized (model 2)
- the stellar wind was assumed to possess a helical *B*-field (described by the Parker solution), while there was no magnetic field in the ISM (model 3)

Gvaramadze et al. 2018

Vela X-1

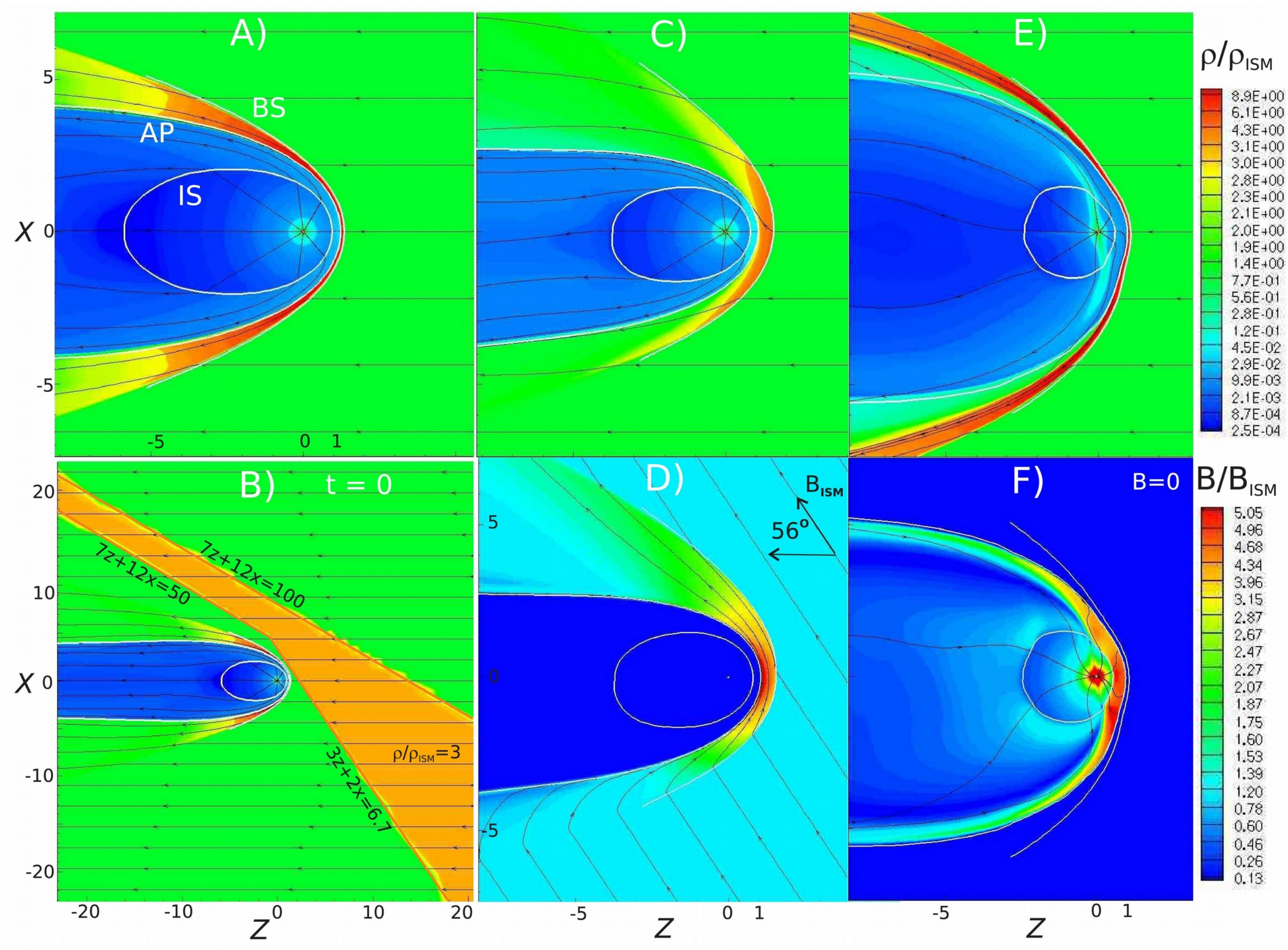
donor star: B0.5 Ia
$R_* = 30\ R_{sun}$
separation = $53.4\ R_{sun}$
v_∞=700 km/s
v_{orb}=200 km/s
=> helical B-field perpendicular to the orbital plane



Krticka et al. 2012

Circumstellar structures around Vela X-1

model 1 model 2 model 3

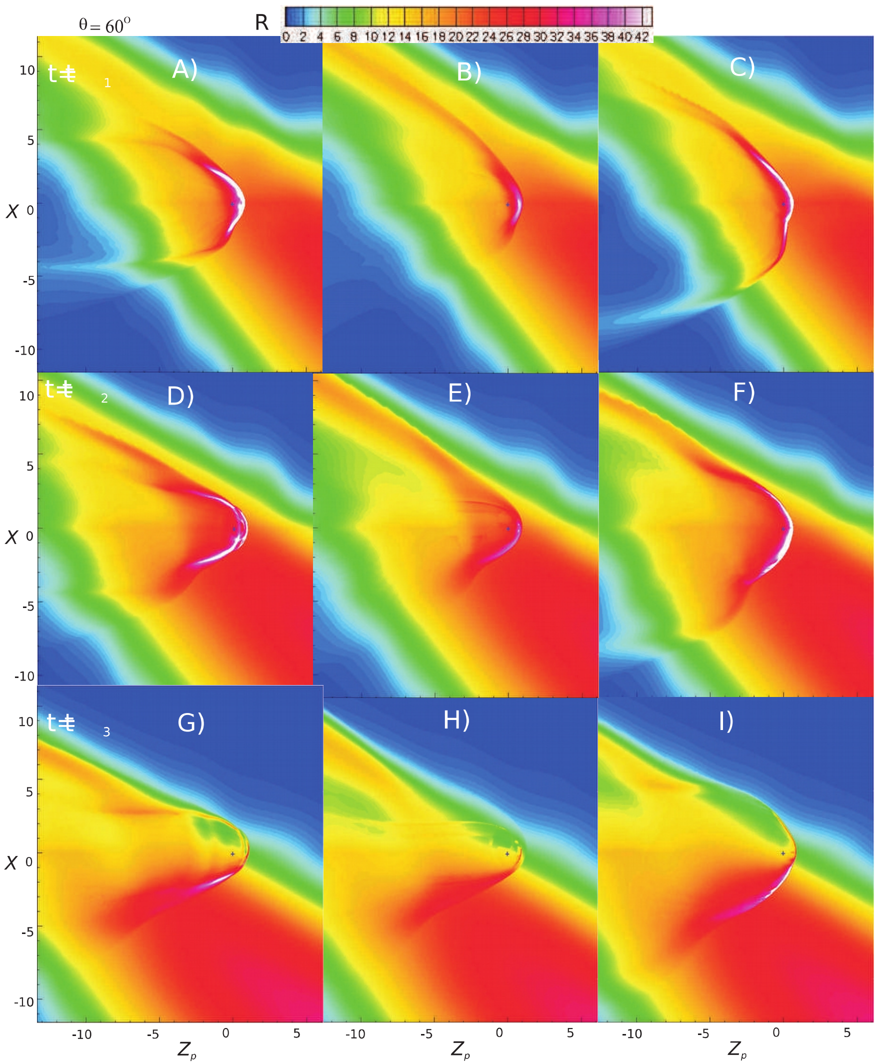


Projection of synthetic Hα intensity maps

t_1 = 93 800 yr

t_2 = 187 600 yr

t_3 = 281 400 yr



model 1 model 2 model 3

θ=60°

Circumstellar structures around Vela X-1

The geometry of the structures around Vela X-1 suggests that this HMXB has encountered a wedge-like layer of enhanced density on its way and that the shocked material of the layer partially outlines a wake downstream of Vela X-1. We found that only a model with the (spiral) stellar magnetic field can reproduce not only the wake behind Vela X-1, but also the general geometry of the bow shock ahead of it.

Thank you!